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The Sys-Rem Detrending Algorithm: Implementation and Testing

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Abstract. Sys-Rem (Tamuz, Mazeh & Zucker 2005) is a detrending algorithm designed to remove systematic effects in a large set of lightcurves obtained by a photometric survey. The algorithm works without any prior knowledge of the effects, as long as they appear in many stars of the sample. This paper presents the basic principles of Sys-Rem and discusses a parameterization used to determine the number of effects removed. We assess the performance of Sys-Rem on simulated transits injected into WHAT survey data. This test is proposed as a general scheme to assess the effectiveness of detrending algorithms. Application of Sys-Rem to the OGLE dataset demonstrates the power of the algorithm. We offer a coded implementation of Sys-Rem to the community.

1. Introduction

Since the discovery that the planet orbiting HD 209458 (Mazeh et al. 2000) transits the disk of its host star (Charbonneau et al. 2000; Henry et al. 2000), many photometric searches for transits have been put into operation (e.g., Horne 2003). However, till September 2006 the yield of these searches was surprisingly small. Only the realization that systematic effects and red noise (Pont, Zucker & Queloz 2006) are an impediment to transit detection explained why many searches detected less planets than expected. The work of Pont, Zucker & Queloz (2006) sharpened the need to account for the presence of red noise in the survey data. Sys-Rem (Tamuz, Mazeh & Zucker 2005), an algorithm to remove systematic effects in large sets of lightcurves obtained by photometric surveys, is designed exactly to answer this need. The algorithm can detect any effect that appears linearly in many lightcurves obtained by the survey. Recently, Sys-Rem, together with other detrending algorithms such as TFA (Kovács, Bakos & Noyes 2005), have become standard tools in transit survey lightcurves processing, contributing already to the recent detection of several transits (Bakos et al. 2006;

Collier Cameron et al. 2006). This paper discusses the implementation of Sys-Rem and suggests a way to assess its performance.

Section 2 reviews the principles of Sys-Rem and Section 3 presents our stopping criterion, a parametrization to determine the number of effects to remove. In Section 4 we propose a test to assess the effectiveness of detrending algorithms and apply it to Sys-Rem. Section 5 discusses the application of the algorithm to the OGLE survey. We conclude with some remarks.

2. The principle of Sys-Rem

We first started to develop our algorithm in an attempt to correct for atmospheric extinction, with an approach similar to that of Kruszewski & Semeniuk (2003). We derived the best-fitting airmasses of the different images and the extinction coefficients of the different stars, without having any prior information on the stellar colours. However, the final result is a general algorithm to deal with any linear systematic effects. In some restricted cases, when one can ignore the different uncertainties of the data points, this algorithm reduces to the well-known Principal Component Analysis (Murtagh & Heck 1987, Ch. 2). However, when the uncertainties of the measurements vary substantially, as is the case in many photometric surveys, PCA performs poorly relative to Sys-Rem.

The principles of Sys-Rem can be easily explained using the original problem we tried to solve. Colour-dependent atmospheric extinction is an obvious observational effect that contaminates ground-based photometric measurements. This effect depends on stellar colours, which are not always known. To correct for the atmospheric extinction one can find the effective colour of each star, which characterizes its variation as a function of the airmass of the measurements.

Specifically, consider a set of N lightcurves, each of which is derived from M images. Define the residual of each observation, r_{ij} , to be the average-subtracted stellar magnitude of the i -th star derived from the j -th image, taken at the airmass a_j . We can then define the effective extinction coefficient c_i of star i to be the slope of the best linear fit to the residuals of this star as a function of the corresponding airmasses, aiming to remove the product $c_i a_j$ from each r_{ij} . In fact, we search for the best c_i that minimizes the expression

$$S_i^2 = \sum_j \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2} , \quad (1)$$

where σ_{ij} is the uncertainty of r_{ij} . Note that the derivation of each c_i is independent of all the other c_i 's, but does depend on all the a_j 's.

The problem can now be turned around. Since atmospheric extinction might depend not only on the airmass but also on weather conditions, we can ask ourselves what is the best estimate of the airmass of each image, given the known effective colour of each star. Thus, we can look for the a_j that minimizes

$$S_j^2 = \sum_i \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2} , \quad (2)$$

given the previously calculated set of $\{c_i\}$. We can now recalculate new best-fitting coefficients, c_i , for every star, based on the new $\{a_j\}$, and continue iteratively. We thus have an iterative process which in essence searches for the two sets – $\{\bar{c}_i\}$ and $\{\bar{a}_j\}$, that best account for the atmospheric extinction.

Many simulations have shown that this iterative process converged to the same $\{\bar{a}_j\}$ and $\{\bar{c}_i\}$, no matter what initial values were used. Therefore, we suggest that the proposed algorithm can find the most suitable effective airmass of each image and the extinction coefficient of each star.

The algorithm, in fact, finds the best two sets of $\{c_i ; i = 1, N\}$ and $\{a_j ; j = 1, M\}$ that minimize the *global* expression

$$S^2 = \sum_{ij} \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2} . \quad (3)$$

Therefore, although the alternating 'criss-cross' iteration process (Gabriel & Zamir 1979) started with the actual airmasses of the different images, the values of the final set of parameters $\{\bar{a}_j\}$ and $\{\bar{c}_i\}$ are not necessarily related to the true airmass and extinction coefficient. They are merely the variables by which the global sum of residuals, S^2 , varies linearly most significantly. They could represent any strong systematic effect that might be associated, for example, with time, temperature or position on the CCD. This algorithm finds the systematic effect as long as the global minimum of S^2 is achieved.

Now, suppose the data are affected by a few different systematic effects, with different $\{c_i\}$ and $\{a_j\}$. Sys-Rem can be applied repeatedly, until it finds no more *significant* linear effects in the residuals.

3. The halting problem

Formally, the process of identifying additional 'systematic' effects in any set of lightcurves can be applied till there is no variation left in all lightcurves. To prevent such a situation, it is obvious that Sys-Rem needs a stopping criterion, which will enable it to remove the strong systematic effects in the data without removing the signal of the variable stars, the transit signals in particular.

Our stopping criterion is based on a measure of the strength of each effect in each lightcurve. We therefore define β as the fractional r.m.s. removed by subtracting the effect from a specific lightcurve. We assume that a significant effect yields a large β . Note that β is defined independently for each lightcurve and each effect. Our stopping mechanism involves choosing β_{min} , so that we apply Sys-Rem subtraction only to effects and lightcurves with $\beta \geq \beta_{min}$.

In order to estimate β_{min} we use the value of β found in a set of randomly generated lightcurves of similar noise structure as the real ones. For each lightcurve in a given dataset we generate a corresponding random lightcurve with a randomization technique, by which we keep the stellar intensities but randomly permute the timing on all measurements. Such a procedure should get rid of any correlated noise hidden in the original lightcurves, while keeping the level of the white noise. We then apply Sys-Rem to the entire set of false lightcurves, find a Sys-Rem effect in this randomized matrix, and calculate for

each false lightcurve its β value. We use the distribution of the β values of the false lightcurves to derive β_{min} , which is the β value for which a fraction α of the random lightcurves have smaller values of β . Therefore, β_{min} is a monotonic increasing function of α . Choosing α of say, 0.9, means removing only effects that are stronger than 90 percent of all random effects. In Section 4 we try various values of α and find that 0.9 is indeed a good choice for the WHAT dataset.

4. Assessing the performance of a detrending algorithm

We propose here a general scheme to test the performance of detrending algorithms. The test is performed on simulated data which have been generated by injecting simulated transit signals into real data. The test is conducted by applying the detrending algorithm to the simulated data and then searching for transits. A transit search applied after an effective detrending algorithm should detect a large fraction of the injected transits, and should *not* yield many 'false positive' transits that had not been injected into the data.

The test proposed here deserves two comments at this stage. The first is related to the assumption that the real data do not include many real transits. Even an accurate set of lightcurves can include at most only very few transits, so the evaluation of the test should not be thwarted by the presence of real transits. The second comment has to do with the fact that the test we propose really checks the effectiveness of the detrending algorithm *together* with the transit detection technique, applied to a specific dataset. Therefore, this test does not assess the overall performance of a detrending algorithm, but only its usefulness when applied to a specific dataset and used in conjunction with a particular transit detection algorithm.

The detection of a transit candidate in a set of lightcurves is never an absolute result, and each transit candidate is likely to be a false positive with some probability. Therefore, any transit survey inevitably outputs a list of transit candidates, prioritized according to some statistic. Thus, we expect an effective detrending algorithm, Sys-Rem or other, to increase the priority of the real transits in the candidate list, reducing the number of false positives and making follow-up more efficient.

To test how well Sys-Rem performs we injected simulated transit signals into some of the lightcurves of WHAT field no. 236 (Shporer et al. 2006). We ran the BLS transit detection algorithm (Kovács, Zucker & Mazeh 2002) on all lightcurves, including the ones with no transit signal, and constructed a candidate list. We repeated this procedure after applying Sys-Rem, with three different values of α .

Fig. 1 shows the fraction of injected transits that were detected by BLS and appear at the top of the candidate list. The detection fraction of the injected transits depends on how far down the list of candidates one goes. Therefore, the figure presents the detection fraction as a function of the number of false detections included in the top of the list. In other words, the figure shows what fraction of the simulated injected transits one could detect if he is ready to include a given number of false positive cases. The higher the graph is, the higher is the probability to include the transit in the top of the list.

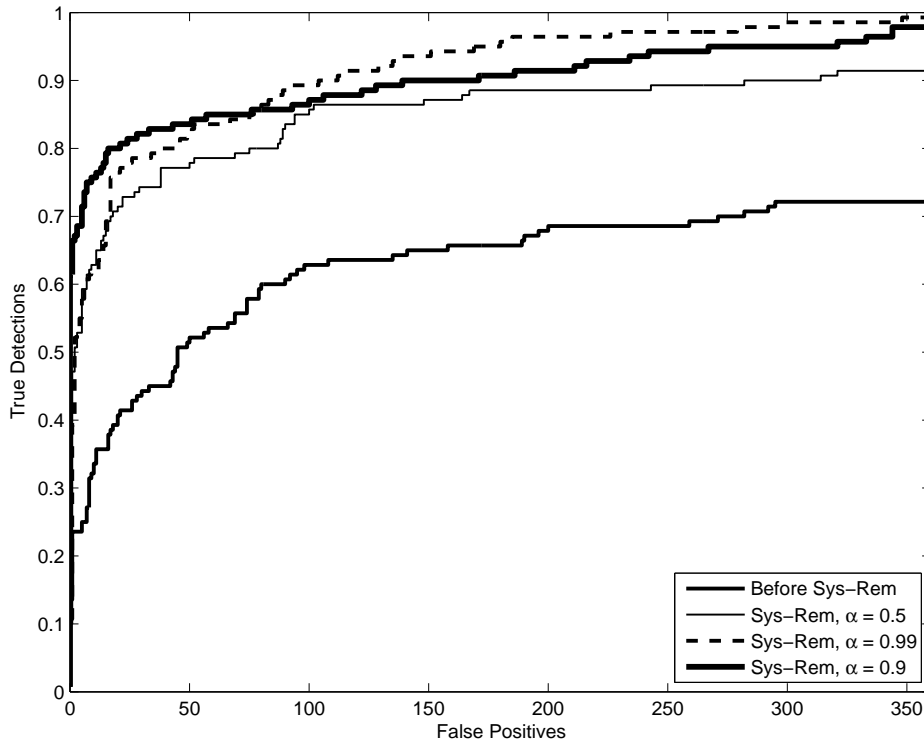


Figure 1.: Fraction of transits detected vs. number of false detections, for different values of α .

The figure shows that applying Sys-Rem with any of the three values of α dramatically improved the detectability of the injected transits. It seems as if for this specific data set and this specific set of injected transits, Sys-Rem with $\alpha = 0.5$ is inferior to the other two options. Because of the limited observational resources, most of the present follow-up projects can not allow a high number of false positive cases, and therefore it seems that Sys-Rem with $\alpha = 0.9$ is the best of the three options tested here.

Note that the number of false positive transits included in the top of the list depends on the data, its red noise distribution in particular. Therefore the meaning of the figure is limited to the WHAT set of lightcurves.

5. Application to OGLE

We applied Sys-Rem to the photometric data collected by the OGLE survey in three Carina fields: CAR100, CAR104 and CAR105 (Udalski et al. 2002). This dataset includes 1200 measurements of about one million stars. In each field, we applied Sys-Rem separately to each of the 8 CCD chips.

To present the effectiveness of Sys-Rem's application to the OGLE data we present in Fig. 2 and Fig. 3 some results from the data of chip 8 in field CAR105. We selected 200 bright stars from the chip, calculated AoV peri-

odograms (Schwarzenberg-Czerny 1989) for each, and then averaged the periodograms to produce the upper panel of Fig. 2. The averaged periodogram shows clearly a periodicity of 1 day and its harmonics, and some low-frequency power. Obviously, this has to do with some systematic effects.

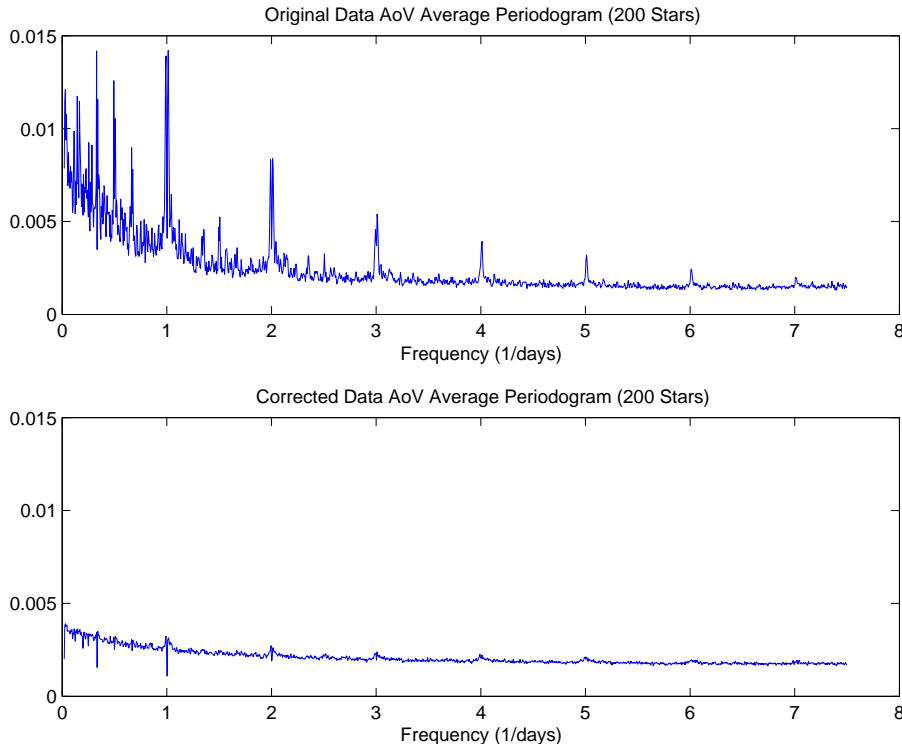


Figure 2.: Averaged AoV periodograms of 200 OGLE stars before (upper panel) and after (bottom panel) applying Sys-Rem

We generated a similar averaged periodogram after we applied Sys-Rem, to produce the bottom panel. As is evident, Sys-Rem removes not only periodic variability with frequencies with integer number of cycles per day, but also most of the low-frequency variability. Note, however, that some troughs appear in one day harmonics, which indicate that Sys-Rem may have removed some true signal along with the systematics, impairing detection of transits in these frequencies. Kruszewski & Semeniuk (2003) got similar results when they searched for systematics with periodicity of one day and its harmonics.

Fig. 3 shows, for the same chip, the *fractional* change in the RMS scatter obtained by Sys-Rem (in percentage of the initial scatter), as a function of the magnitude and the original scatter. The top panel of the figure shows that Sys-Rem is most effective in reducing the scatter of the brighter stars, where the systematic noise is more dominant. For those stars the improvement can get up to 30% of the original scatter. Note that a small but substantial improvement can be seen for all stars. The increase of Sys-Rem improvement for the faint stars is probably due to removal of systematics associated with background subtraction.

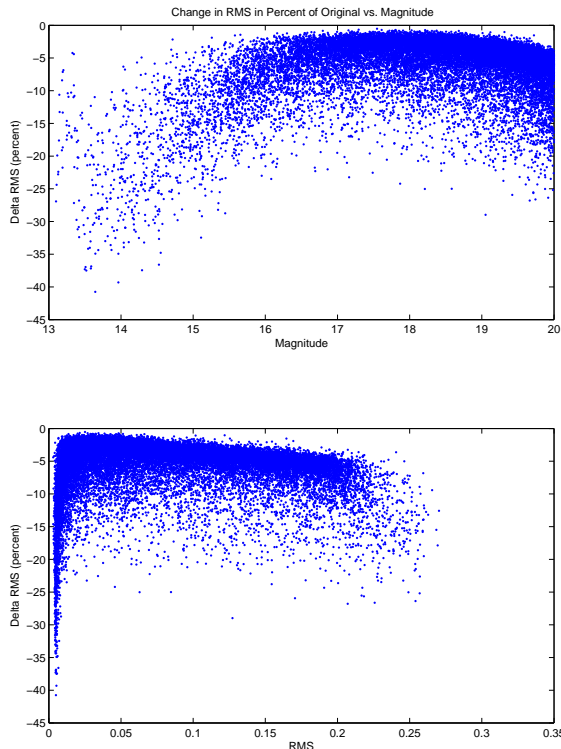


Figure 3.: The reduction in the RMS scatter of the OGLE lightcurves as a function of the magnitude (upper panel) and the initial scatter

6. Conclusion

We have presented a stopping criterion of Sys-Rem, based on the fraction of the variability subtracted from any lightcurve by removing the systematic effect. This power is compared with the power subtracted from random lightcurves with the same noise level. The comparison is parameterized, so a different threshold of removing fractional variability can be adopted. We assessed the performance of Sys-Rem on simulated transits injected into the WHAT survey dataset and found that Sys-Rem improved the detectability substantially. This is true for all three values of the stopping parameter used. We propose this test as a general scheme to assess the effectiveness of detrending algorithms.

We have presented an application of Sys-Rem to the dataset of the OGLE transit search. We demonstrated that the algorithm can eliminate a significant part of the systematic noise hidden in the light curves. The mainly affected stars are the brighter ones, where the photon noise is less significant and the systematics grow in importance.

In a previous conference we (Mazeh et al. 2006) offered the community an 'overnight cleaning service', through which we apply our Sys-Rem code to their photometric data and return the data clean of systematics, ready for search for minute periodic variability. It turned out that most researches do not like their laundry to be cleaned by others. Therefore, we are now offering the community

to acquire their own cleaning facility: the code is available in C and can be obtained upon request from omert@wise.tau.ac.il.

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